

Active Sway Damping for Cable-Suspended Robotic Systems with CERN Human Robot Interface Integration

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Abstract—This paper presents a novel Human-Robot Interface integrated control strategy for suppressing oscillations in cable-suspended robotic systems, specifically the CRANEBot at CERN. The approach leverages the robot's arms to actively dampen oscillations through energy dissipation at each cycle, eliminating the need for modifications to the suspension platform. Experimental results demonstrate the effectiveness of the proposed method in reducing settling times and enhancing operational stability, showcasing its potential for applications in complex and hazardous environments.

Index Terms—Cable-suspended robots, Sway Damping, Human-Robot Interface, Robotic Telemanipulation

I. INTRODUCTION

Working in radioactive environments, such as those at European Organisation for Nuclear Research (CERN), demands robotic telemanipulation to ensure operational safety and efficiency [1], [2], [3]. Cable-suspended systems, such as CERN's CRANEBot [4], [5], shown in Fig. 1, address this need by enabling versatile operations at varying heights with minimal environmental disturbance. These systems not only extend the operational workspace but also mitigate the risks associated with manipulator-environment interactions [6], [7]. Furthermore, the use of cables significantly reduces the overall weight compared to rigidly connected configurations, enhancing safety and improving energy efficiency in constrained environments. However, cable-suspended systems are prone to pendulum-like oscillatory behaviour during transport due

to dynamic coupling and external forces [8], [9], [10]. These oscillations can lead to prolonged settling times, delaying task execution, and pose potential collision risks with the surrounding environment [11]. Therefore, developing effective strategies to mitigate these oscillations without requiring modifications to the existing infrastructure is essential for the practical deployment of such systems.

The underactuated nature of these systems, characterised by passive cable joints, complicates the control and stabilisation process. Specifically, for the CRANEBot operating at CERN, where modifying the crane's control system is often impractical or inconvenient, it is crucial to develop oscillation suppression techniques that rely solely on the actuation of the robot's arms. Addressing this challenge is vital for ensuring the efficient and safe operation of cable-suspended robots in complex and demanding environments.

The mitigation of oscillations in cable-suspended systems has been a subject of extensive research. A common approach involves controlling the motion of the suspension platform, with various techniques such as input shaping [12], [13] [14], and closed-loop methods [15], [16] including Model Predictive Control (MPC) [17], [18], being widely explored. Another approach involves utilising the additional actuated masses on the suspended load itself for oscillation suppression, although this often necessitates significant hardware modifications [19], [20]. Recent research efforts have focused on exploiting the capabilities of robotic manipulators to suppress

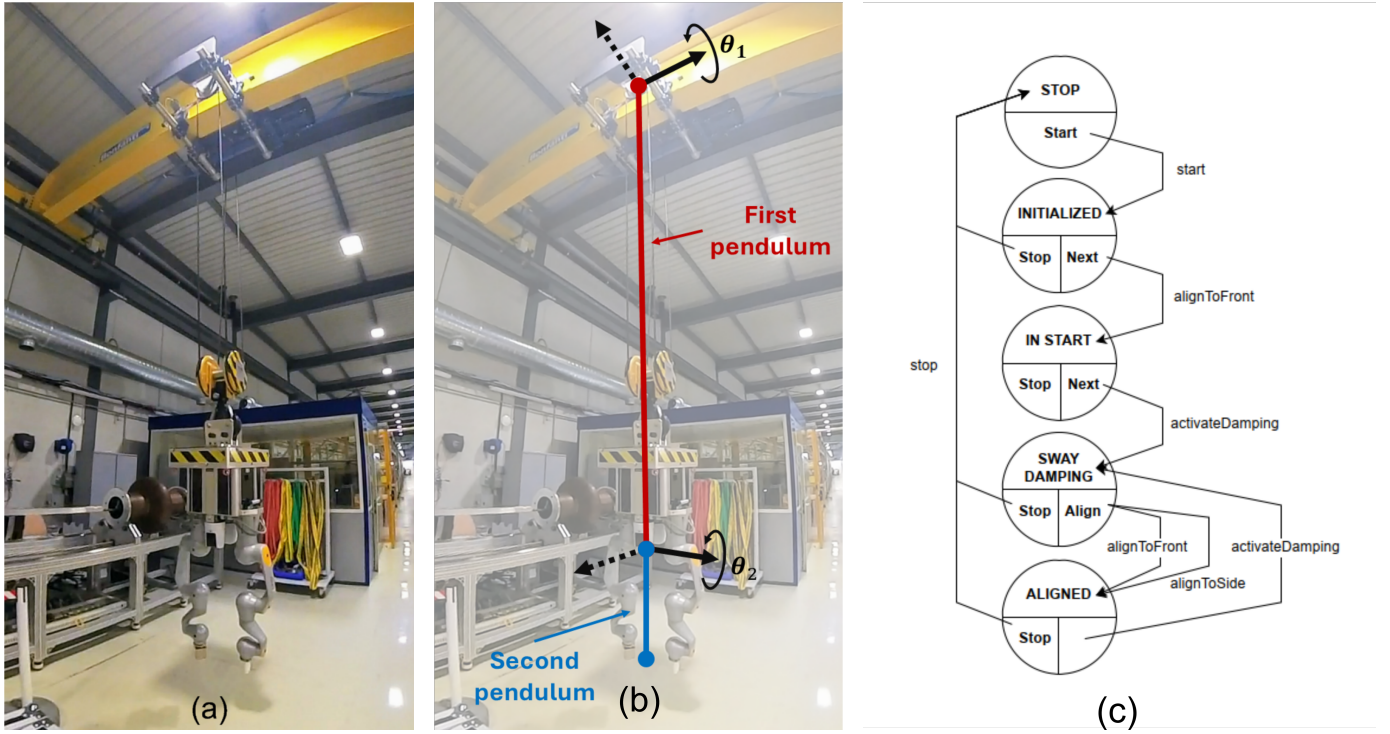


Fig. 1. (a) CRANEBot, crane-suspended robotic system for inspection and maintenance at CERN (b) Graphical representation of the two pendulums in which the robot can be decomposed (c) The state machine which regulates initialisation of the control, alignment along the oscillation plane, and activation of the sway damping control

oscillations, with methods such as passivity-based control [21], model-free approaches [22], [23], partial-feedback linearization [24] and Nonlinear MPC [25] being investigated. Among these, energy-based control offers an attractive balance of simplicity, robustness, and physical grounding, since it directly exploits the natural energy exchange of the suspended system. In contrast to predictive approaches such as MPC, which rely on accurate system models and considerable computational resources, the energy-based method requires only minimal sensing and lightweight computation, making it more reliable for real-time teleoperation in hazardous environments. This makes it especially suited for scenarios like CRANEBot, where modifications to the crane infrastructure are not possible and operational robustness is critical. However, the implementation of energy-based control techniques, integrated with Human-Robot Interfaces, for systems like the CRANEBot remains largely unexplored. This paper aims to bridge this gap by introducing a novel control strategy that leverages the CRANEBot's arms to dissipate oscillation energy, validated through the CERN Human Robot Interface, offering a practical and effective solution without requiring modifications to the existing infrastructure.

II. TECHNICAL APPROACH

A. Sway Damping Control

To ensure safe operation, crane safety guidelines dictate that loads must be moved perpendicularly, with oscillations settling before any directional change [26], [27]. This operational

framework enables a focused examination of planar oscillation scenarios. Crane cables, considered rigid and inextensible, behave as a single rigid body [10]. Building on these physical principles, the system can be conceptualised as a double pendulum extending from the upper suspension point to the dual-arm robot's end-effectors. The first pendulum segment connects the suspension point to the robot arm shoulder joints, while the second segment extends to the end-effectors, as shown in Fig. 1. This structure creates an underactuated system due to the lack of direct actuation at the upper suspension point. The primary control objective is to return this point to its equilibrium faster than would occur through natural damping processes alone.

To address this control challenge, we leverage the energy absorption capabilities of the second pendulum, which plays a critical role in the damping mechanism. Optimal damping occurs when both pendulums operate at the same frequency, due to dynamical limits, with an appropriate phase relationship, specifically, a phase shift of approximately 90 degrees enables the second pendulum to effectively counteract the first pendulum's motion. This energy transfer mechanism enhances the system's overall energy dissipation efficiency beyond what friction alone could achieve. Through this pendulum interplay, the system achieves more efficient damping as the second pendulum generates forces that oppose the primary pendulum's movement, progressively reducing its amplitude.

Let m_1, m_2 be the masses, l_1, l_2 the lengths, and I_1, I_2 the moments of inertia of the first (passive) and second (active)

pendulum, respectively. Defining their angles $\theta_1(t), \theta_2(t)$ relative to vertical, and g is the acceleration due to gravity.

The Lagrangian $\mathcal{L} = T - V$ is defined using kinetic energy

$$T = \frac{1}{2}m_1(\dot{x}_1^2 + \dot{y}_1^2) + \frac{1}{2}I_1\dot{\theta}_1^2 + \frac{1}{2}m_2(\dot{x}_2^2 + \dot{y}_2^2) + \frac{1}{2}I_2\dot{\theta}_2^2 \quad (1)$$

and potential energy

$$V = -m_1gl_1 \cos(\theta_1) - m_2g(l_1 \cos(\theta_1) + l_2 \cos(\theta_2)) \quad (2)$$

where

$$\begin{aligned} x_1 &= l_1 \sin(\theta_1), & y_1 &= -l_1 \cos(\theta_1), \\ x_2 &= l_1 \sin(\theta_1) + l_2 \sin(\theta_2), & y_2 &= -l_1 \cos(\theta_1) - l_2 \cos(\theta_2). \end{aligned}$$

Applying the Euler-Lagrange equation, $\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{\theta}_i} \right) - \frac{\partial \mathcal{L}}{\partial \theta_i} = 0$, yields the equations of motion (neglecting centrifugal and Coriolis terms under small-angle and low-velocity assumptions):

$$\begin{cases} m_1 l_1^2 \ddot{\theta}_1 + m_2 l_1^2 \ddot{\theta}_1 + m_2 l_1 l_2 \ddot{\theta}_2 \cos(\theta_1 - \theta_2) \\ \quad + g(m_1 l_1 + m_2 l_1) \sin(\theta_1) = 0, \\ m_2 l_2^2 \ddot{\theta}_2 + m_2 l_1 l_2 \ddot{\theta}_1 \cos(\theta_1 - \theta_2) + m_2 g l_2 \sin(\theta_2) \\ \quad = u(t) \end{cases} \quad (3)$$

where $u(t)$ is the control input for the second pendulum.

We define the instantaneous power transferred from pendulum 1 to pendulum 2 as the rate of work done by the generalized coupling torque acting on θ_1 due to θ_2 (equivalently, the negative of the rate of work done on θ_1 by pendulum 2). The generalized power associated with coordinate θ_1 is $\tau_1 \dot{\theta}_1$ where τ_1 is the generalized torque on θ_1 . From the first line of (3), the term proportional to $\dot{\theta}_2$ is precisely the interaction (coupling) torque exerted by the second pendulum on the first,

$$\tau_{2 \rightarrow 1} = -m_2 l_1 l_2 \ddot{\theta}_2 \cos(\theta_1 - \theta_2). \quad (4)$$

Hence, the power flowing out of pendulum 2 and into pendulum 1 (energy transfer rate) is

$$\begin{aligned} P_{\text{transfer}}(\theta_1, \theta_2, \dot{\theta}_1, \dot{\theta}_2) &\triangleq \tau_{2 \rightarrow 1} \dot{\theta}_1 = \\ &-m_2 l_1 l_2 \ddot{\theta}_2 \cos(\theta_1 - \theta_2) \end{aligned} \quad (5)$$

Assuming small angle oscillations, with $\theta_1(t) = A_1 \cos(\omega t)$ and $\theta_2(t) = A_2 \cos(\omega t + \Delta\phi)$, where $\Delta\phi$ is the phase difference, the power transfer simplifies to

$$\begin{aligned} P_{\text{transfer}} &\propto \sin(\omega t) \cos(\omega t + \Delta\phi) \\ &= \frac{1}{2} [\sin(2\omega t + \Delta\phi) + \sin(\Delta\phi)] \end{aligned} \quad (6)$$

Maximising the time-averaged power transfer requires maximising the time-independent term $\sin(\Delta\phi)$. Thus, $\Delta\phi = \frac{\pi}{2}$ optimises energy transfer. This quarter-cycle phase shift ensures the second pendulum reaches equilibrium when the first is at maximum displacement, optimising energy exchange and enhancing damping efficiency. While the term $\sin(2\omega t + \Delta\phi)$ contributes to instantaneous power fluctuations, its average value over a cycle is zero and therefore does not contribute to long-term energy exchange.



Fig. 2. CERN Human Robot Interface showing the sway damping control integration with the following elements on the scene: (a) The control panel, (b) The oscillation estimator status feedback messages, and (c) The sway damping status feedback messages.

B. Software Integration and Human-Robot Interface

Effective control requires a robust estimation system to determine the oscillation state of the system. The developed oscillation estimator utilises an Inertial Measurement Unit (IMU) to accurately capture critical oscillation parameters: the oscillation angle (for both roll and pitch axes as shown in Fig. 1), oscillation period, and the primary oscillation plane direction (whether aligned with the bridge or trolley of the overhead crane). Based on this estimator, we designed a controller implemented as a finite state machine (illustrated in Fig. 1). This state machine manages system initialisation, initial arm positioning (the reference position around which the arms perform counteracting movements to suppress oscillations), arm rotation to align with the main oscillation plane (as determined by the estimator), and finally, activation of the sway suppression mechanism. The finite state machine effectively functions as an outer control loop, primarily regulating alignment with the oscillation plane. For the inner control loop, i.e., the actual sway damping control, the critical 90-degree phase shift is achieved by utilizing angular feedback from the estimator for the axis with the greatest oscillation, i.e., θ_1 , and sending a velocity command to the second shoulder joint of the manipulators, i.e., $\dot{\theta}_2$, proportional to the oscillation angle. This proportionality between the second pendulum's velocity and the first pendulum's angular position ensures the desired phase shift. To guarantee smooth velocity that remains within system limits, the position feedback passes through a hyperbolic tangent function with an adjustable gain k to control the slope of the linear portion of the function, i.e. $\dot{\theta}_2 = \tanh(k\theta_1)$. The system progresses through multiple operational states (Stop, Initialised, InStart, Aligned, and SwayDamping) with transitions triggered by specific events. Starting from the inactive Stop state, the controller advances through initialisation and alignment before reaching the SwayDamping state, where it continuously adjusts joint velocities to minimise oscillations by implementing the energy transfer principles described in our theoretical model. This structured

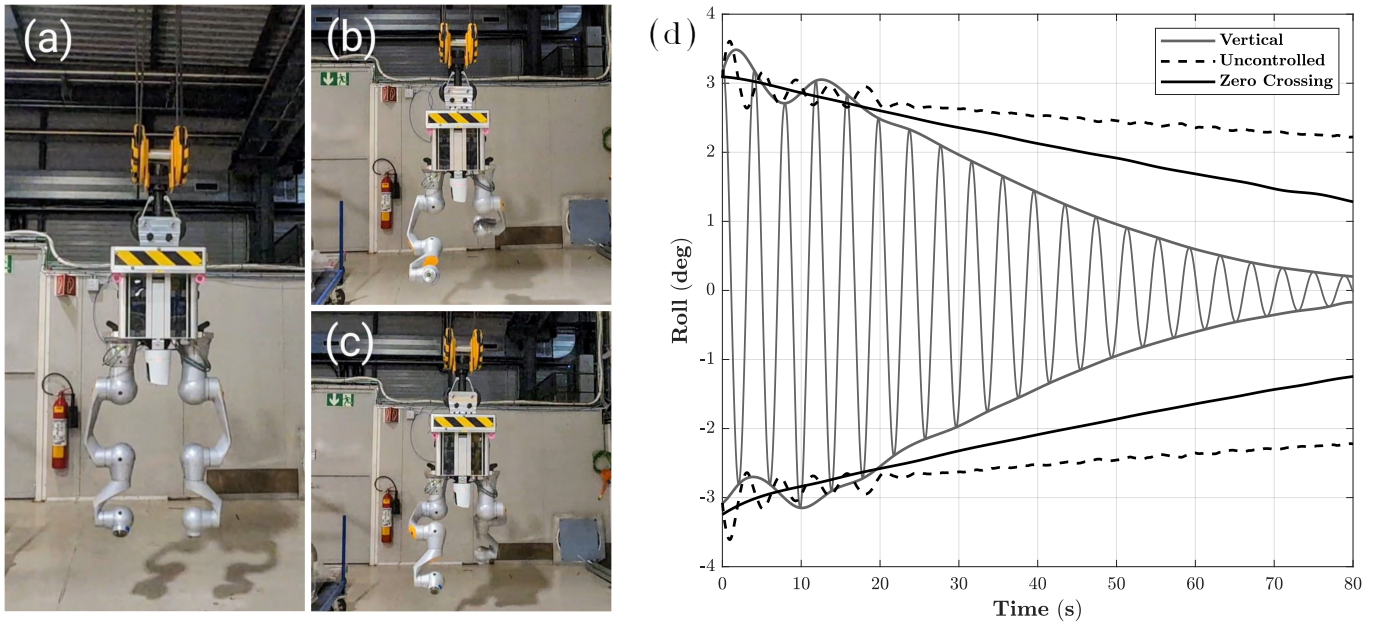


Fig. 3. The three home configurations: (a) vertical, (b) extended, (c) custom. (d) Comparison between energy-based and zero-crossing approaches, where “Vertical” represents the oscillation with the proposed energy-based control strategy; “Uncontrolled” represents free oscillation (energy-based); and “Zero Crossing” represents the thicker function with the state-of-the-art method.

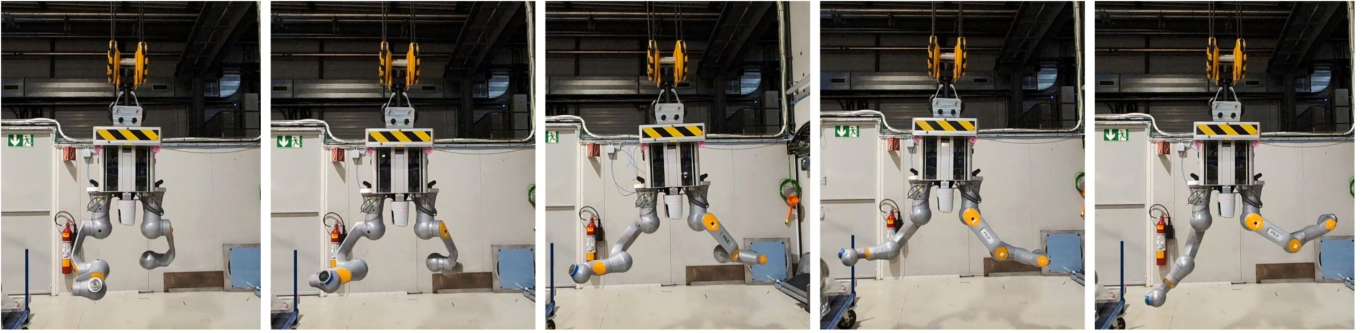


Fig. 4. Arms alignment along the oscillation plane, and activation of the sway damping control action.

approach creates a robust implementation capable of adapting to varying operational conditions while maintaining optimal damping performance.

The entire system is integrated within the CERN Robotic Framework (CRF), a modular C++ software architecture developed for teleoperation and autonomous inspection in hazardous environments [28]. This framework manages all aspects of robot control from low-level drivers to user interface communication. Operators interact via the CERN Human Robot Interface, a Unity-based mixed-reality GUI that provides real-time video, 3D visualisation, and remote control over 4G/5G, WiFi, or wired networks [29], [30]. As shown in Fig. 2, the interface includes a control panel for activating sway damping, configuring arms home position, and adjusting the control gain. Status panels display real-time feedback from the oscillation estimator and sway damping control, allowing users to reset the estimator, set the oscillation direction, and monitor damping performance. The interface also manages state transitions in the sway damping control system (Fig. 1).

Before activation, users must define the initial alignment of the robot, choosing between “bridge” or “trolley”, and configure the robotic arms’ home position (vertical, extended, or custom). Once set, the damping control can be activated, with the interface providing continuous feedback and control adjustments for optimal performance.

III. EXPERIMENTAL RESULTS

CRANEBot, the crane-suspended robotic system for hazardous environments developed at CERN, was equipped with two Pilz PRBT 6 manipulators and a Gable IMU SE3. Experiments were conducted using a BONFANTI 7.5T overhead crane at 4 meters height in CERN building 927. Oscillations were induced by controlled crane movements, and the oscillation estimator and sway damping control were activated through the graphical interface. Tests included different manipulator configurations (see Fig. 3), demonstrating the controller’s adaptability to varying conditions, including changes in suspension height.

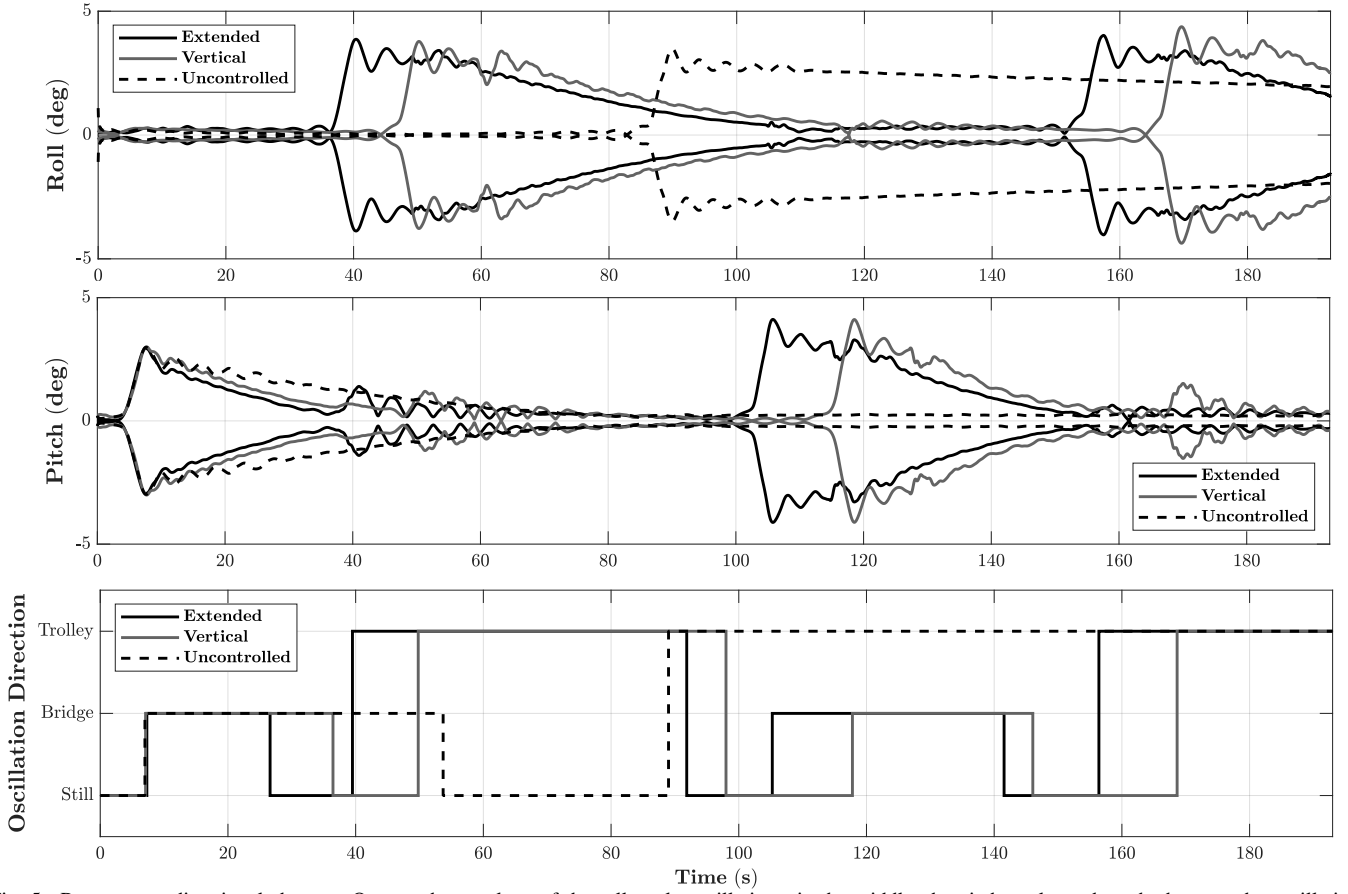


Fig. 5. Response to directional changes. On top, the envelope of the roll angle oscillations, in the middle, the pitch angle, and on the bottom, the oscillation plane detection. The legends "Extended" represents the thicker line and it means active control with home configuration in extended position, "Vertical" represents active control with home configuration in vertical position, and "Uncontrolled" free oscillation.

A comparative analysis was first performed between the proposed energy-based control strategy and a state-of-the-art zero-crossing method, detailed in [23]. Unlike this approach, which activates the robotic arms at each vertical crossing, the energy-based control ensures a precise phase shift for effective damping. Experimental results in Fig. 3 show the envelope of oscillations induced by manual displacement of the platform. The plots demonstrate superior suppression performance of the proposed control method, reducing oscillation amplitude by 84.4% compared to the zero-crossing method and 90.9% compared to the uncontrolled case, while also significantly shortening oscillation duration. Results confirmed that the control system accelerates oscillation damping, particularly in the trolley direction, where natural damping is weaker.

Further tests examined the response of the proposed control to directional changes in overhead crane movement, alternating oscillations between bridge and trolley directions. Fig. 4 shows the alignment of the arms in response to a change in the oscillation plane and the activation of the sway damping control. Fig. 5 shows the oscillation envelopes (separately for roll and pitch) during directional change sequences in both the uncontrolled case (free oscillation) and with active control. In one case, the home configuration is vertical, while in the other, it is extended. As can be seen, activating the control drastically reduces damping times, allowing for more directional

changes compared to the uncontrolled case. The extended arm configuration showed a slight performance advantage over the vertical configuration, achieving faster suppression. Overall, the experimental validation demonstrated the robustness and efficiency of the proposed control approach in real-world conditions, as further illustrated in the video accompanying this paper.

IV. CONCLUSION

This article introduces a Human-Robot Interface integrated control strategy for suppressing oscillations in CERN's CRANEBot, using the robot's manipulators as active dampers. Grounded in an energy-based control principle with a quarter-cycle phase shift, the method was implemented within the CERN Robotic Framework and validated experimentally. Results showed up to 90% reduction in oscillation amplitude and significantly faster settling compared to both uncontrolled motion and state-of-the-art zero-crossing approaches. The approach requires no crane modifications, adapts to different arm configurations, and enhances operational safety during directional changes. These results position energy-based damping via robotic arms as a practical and effective strategy for cable-suspended systems in hazardous environments, with strong potential for future extensions to adaptive and predictive control.

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